

SWELLING AND SHRINKAGE PHENOMENA IN SOILS

Abstract

Swelling and shrinking in soils occur as a result of the changes in volume of soil with the corresponding changes in the soil's water content. The magnitude of swelling and shrinking is determined by the type and quantity of the clay minerals present in the soil. They are important from the point of view of structural engineers as well as for the agriculturalists due to their swell- shrink behaviour. Therefore, it is important to understand the soils showing swelling and shrinking behaviour, the mechanisms behind the behaviour and the consequences due to them. This chapter gives a brief knowledge about the swelling and shrinkage phenomena in soils, their behaviour, the reasons behind their behaviour and the mechanisms responsible for it, as well as how to measure the swell-shrink potential of the soils.

Keywords: Swelling, shrinkage, soil water content, plasticity, consistency, clay minerals, shrinkage limit.

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I. INTRODUCTION

The specific volume change of soil in association with the water content in soil is defined as soil shrinkage, and it is mainly a result of the properties of swelling in clay (Stirk, 1954). This process when reversed with the changes in water content is called as swelling, which is a reverse of shrinkage. The type and quantity of clay, the initial conditions of soil compaction, and additional elements like the depositional environment, which affects both the arrangement of soil particles and overburden pressure as well as the magnitude of weathering, all influence how much there will be a change in volume with a corresponding change in water content (Nelson and Miller, 1997; Yong and Warkentin, 1975). Although to a varying extent, factors that affect swelling are anticipated to also affect shrinking. Shrinkage is the result of the changes in volume of the soil plasma and, to a lesser extent, structural porosity with water content. The plasma is composed of soil colloidal constituents, known as clay matrix. Expansive clay minerals, in particular, expand by absorbing water and contract, or shrink, as they release water and dry out. The ability of clays to absorb water varies according to their structure. 10% expansions are common in the most expansive clays. Because of their shrink-swell behavior, these soils pose a significant risk to structural engineers worldwide, with the mitigation costs of billions of pounds each year. These soils, which are prevalent in arid/semi-arid and humid climate, typically contain some form of clay mineral, such as smectite or vermiculite, and their expansive nature can cause significant damage to the properties and infrastructure.

Shrinkage in soils generally occurs on the surface layers of the soil. The processes that cause a decrease in the content of soil moisture and thus, shrinkage and shrinkage cracks (hairline cracks that are usually less than 2m in length and do not extend across the entire concrete slab) include: (i) evaporation process in dry climates from the soil surface, (ii) low ground water table, (iii) soil desiccation by trees during brief periods of drought in humid environments. As the moisture content in soil decreases, there is an increase in surface tension which leads to an increase in the capillary stress within the pore spaces, which then results in a decrease in the overall soil volume as the increased surface tension makes the adjacent soil particles to pull closer towards each other. As the process continues, the overall soil volume continues to reduce, and there comes a point where there is no further reduction in volume but the magnitude of moisture saturation remains 100%, which is called as the shrinkage limit (SL) (Figure 1). As the climate changes and the shrunken soils regain water, they start swelling. Expanding soils, often referred to as swelling soils, are those that increase in volume when exposed to moisture. Water molecules are drawn into spaces between the soil plates when water is introduced to the expansive soils. The plates are pushed apart as more water is absorbed, increasing the soil pore pressure. This chapter will provide the reader about the mechanisms behind the swelling and shrinking behavior of soils, which is an important phenomenon to be understood for building infrastructures and properties and for agricultural productivity.

II. STATES OF HYDRATION IN CLAY

Normally, clay particles are never in dry state completely. When they are put for 24 hours in an oven at 105°C (standard for drying the soil materials), they still hold certain amounts of water adsorbed in them. This strong affinity for water is due to the hygroscopicity of clay soils, which is described as the capability of clays to sorb and condense water vapor

from the air (Harter, 1986). Even soils which are said to be in 'air-dry' state also have several percent of mass wetness (its exact amount is dependent on the type and amounts of clay present, and humidity of the surrounding air). When the soils are in oven-dry state, water molecules are so tightly held with the clay particles that they are considered as a part of the clay. As water is added to the soils, the films of water surrounding every clay particle thickens and the water molecules added become loosely held. The factor that strongly influences the entire physical behavior (i.e. strength, plasticity, consistency and water and heat conduction) of clay soils is the magnitude or degree of hydration, which is defined as the mass of water in relation to the mass of clay present.

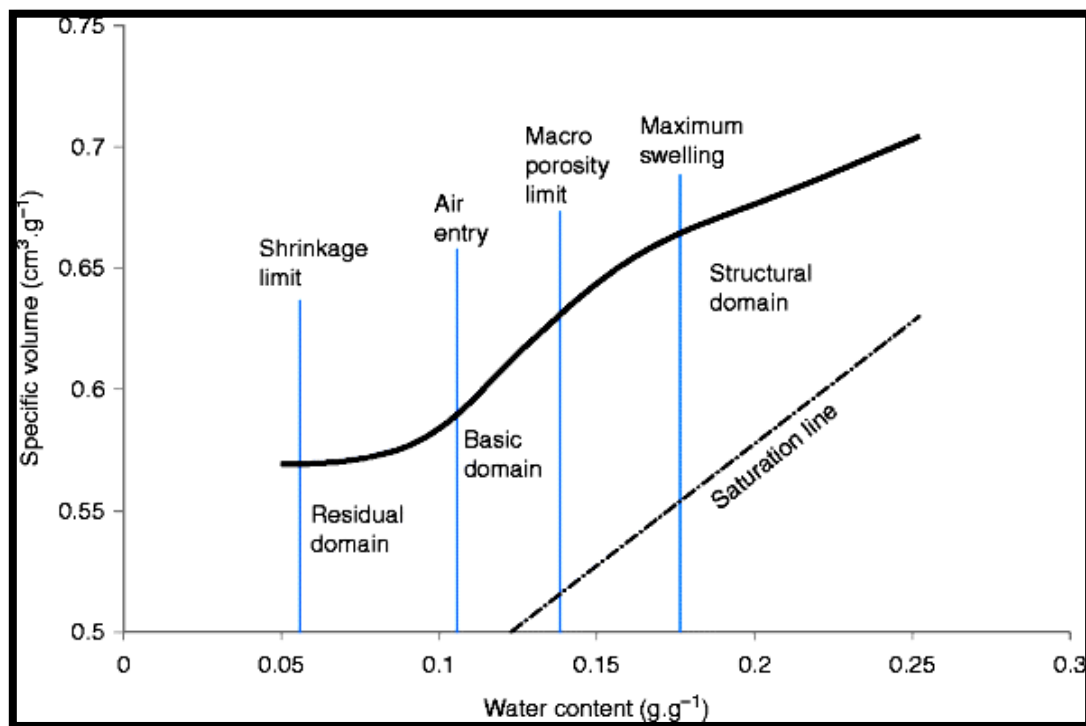


Figure 1: A type of shrinkage curve in an undisturbed sample of soil showing points of transition between shrinkage domains.

III. MECHANISM BEHIND THE SWELLING AND SHRINKAGE BEHAVIOUR

Water gets attached to the surfaces of clay through mechanisms which include:

1. dipolar electrostatic attraction,
2. orientation of water molecules to the charged sites,
3. hydrogen bonding with the oxygen atoms exposed on clay crystals
4. adsorbed cations associated with the clay (it depends on the type of cations present and clay's cation adsorption capacity).

Swelling pressures develop when a confined body of clay is exposed into contact with or is made to sorb water from a solution present externally. The pressure applied to a body of soil, which is exposed for imbibing water, to prevent it from expansion or the the pressure which a soil body exerts on the rigid walls of a container, when it is exposed for imbibing

water from a reservoir at atmospheric pressure is called as swelling pressure. It depends upon the difference in osmotic pressures between the external solution and the adsorbed water. The enveloping water thickness in a partially hydrated micelle is less than the potential thickness of the fully expanded diffuse double layer. If available, the truncated double layer will tend to expand to its full potential thickness and dilution by osmotic absorption of additional water. Each micelle's swarm of positively charged cations repels those of the adjacent micelles as it expands. As a result, the micelles move away from each other causing the whole soil system to swell, which can also lead to closing of larger pores (reducing the system's permeability).

Since there are often twice as many monovalent cations as divalent cations, the osmotic attraction of a clay assemblage for "external" water is typically twice as high with the former. Therefore, swelling is highest in the presence of distilled water as the external solution and monovalent cations like sodium. When calcium occurs as a dominating cation in the exchange complex, there is a great reduction in swelling. The similar effect is caused when trivalent aluminum is present at low Ph. The factors which suppress swelling also includes soil solution with higher salinity. But when a saline soil, having a predominance of sodium salts, gets leached of the excess salts with fresh water, without adding concurrently gypsum or calcium ions, swelling occurs as a result of the higher amounts of sodium ions present in the adsorbed phase.

Therefore, swelling is dependent on:

1. clay mineral present (its type and quantity),
2. specific surface area of clays (generally, swelling increases as the specific surface area increases)
3. soil particles orientation or arrangement,
4. presence of cementation between the particles (by aluminum or iron oxides, carbonates or humus).
5. Depth of layers of soil (when there is swelling of soils in the surface layers on wetting and subsequent shrinking of soils on drying, the underlying layers of soil get prevented from swelling due to the confinement of the upper layer soil, which is called as the overburden pressure).

When a clay body that has been hydrated is dried, shrinkage takes place instead of swelling. When the process of shrinking begins in the field, the surface soil starts forming various cracks, that disrupts the mass of soil into various fragments, which range small microaggregates to macroaggregates and /or large blocks (Figure 2). For example, as occurs in soils rich in montmorillonite clays. When the soil is exposed to alternating wetting and drying, as occurs in semiarid regions, soils start to heave and then settle, which leads to the formation of wide, deep cracks and slanted sheer planes that extend deep into the soil profile.

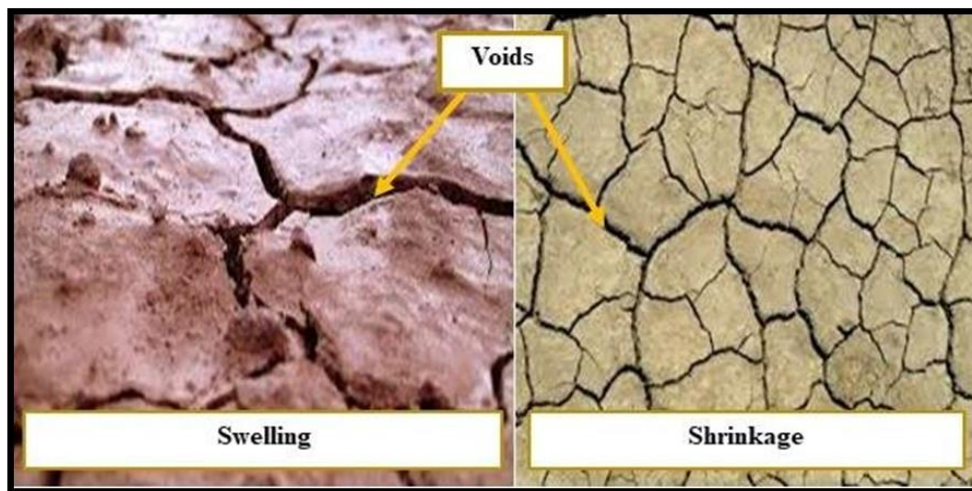


Figure 2: Depicting the status of soil at the time of swelling and shrinkage

The environmental factors that contribute primarily to swelling and shrinking of soils are:

1. seasonal movements caused due to fluctuations of rainfall and vegetation growth;
2. enhancement of seasonal movements due to trees, by severe pruning of trees or by removal of trees or hedges;
3. subsidence for long time when there is development of water deficit for a long time;
4. heave for long time when there is dissipation of a persistent water deficit;
5. Increase in susceptibility of the surface soils due to density reduction.

IV. SWELL- SHRINK BEHAVIOUR

The configuration of the thin crystal lattice layers that clay particles create determines their shape. In shrink-swell clays, water is attracted to and held between the crystalline layers (and on their surfaces) in a firmly bonded "sandwich," according to the molecular structure and arrangement of the clay crystal sheets. Water molecules' electrical dipole structure causes an electrochemical attraction to the microscopic clay sheets. Adsorption is the process by which the water molecules get attached to the clay sheets. Na-smectite clays (montmorillonite) have greater affinity for water and thus, adsorb abundant water molecules between its clay sheets. Theoretically, they can increase in volume by an 800-fold factor, leading to the dispersion of clay platelets by removing repulsive interlayer forces. As a result, they have a significant shrink-swell potential, similar to vermiculite and chlorite, which also show crystalline swelling.

Water molecules between the clay sheets in saturated clay shrink-swell soils cause the bulk volume of the soil to increase or decrease with variations in soil water content (Fig.3). This absorption process loosens the inter-clay bonds, resulting in a decrease in soil strength. As there is reduction in soil moisture due to evaporation or by gravitational forces, the water in between the clay sheets is released leading to an overall decrease in the soil volume, thus causing shrinkage. The process also results in voids and desiccation cracks. Shrinkage and swelling typically take place up to a depth of around 3 m in the near-surface, however this might change depending on the climate. The initial water content, internal structure, void

ratio, type and quantity of clay minerals and vertical stresses in expansive soils, all affect their shrink and swell potential (Bell & Culshaw, 2001). These minerals, which include smectite (montmorillonite, nontronite), illite, vermiculite, and chlorite control the soil's natural expansiveness. Generally, the shrink-swell potential increases with the soil mineral concentration. However, when other non-swelling minerals like quartz and carbonite are present, it may help in mitigating these effects (Kemp et al. 2005).

As long as the soil's water content is fairly constant, even soils with a high shrink-swell potential won't typically pose any problem. This is dependent on the soil mineralogy and water status, variations in water content, and the rigidity and geometry of a building built upon it (Houston et al. 2011). Suction or variations in water content in a soil saturated partially enhance the risk of harm, while clay mineralogy in a soil saturated fully regulates the behavior of swelling and shrinkage.

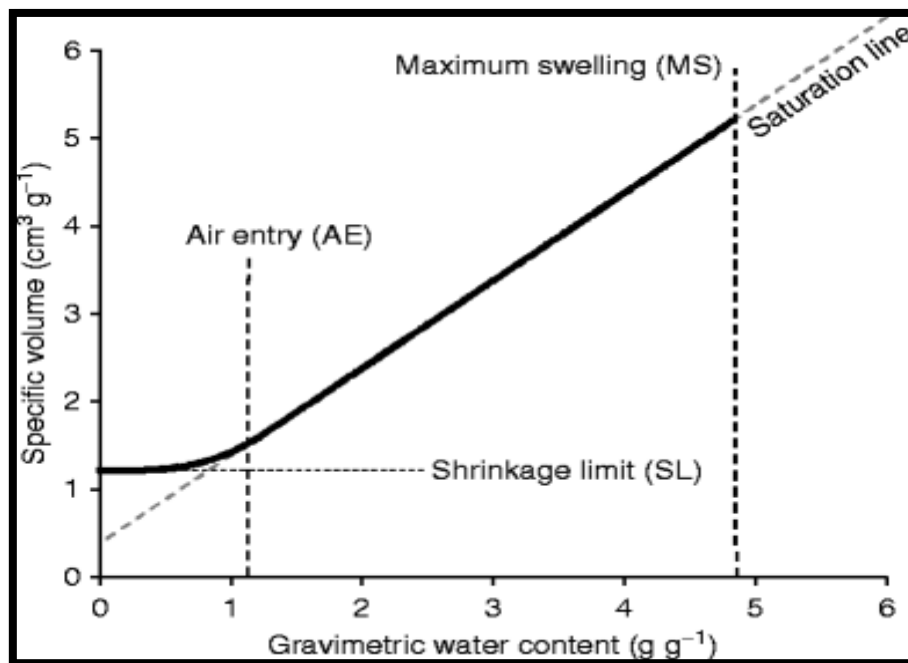


Figure 3: A type of Shrinkage Curve in Clay Soils Depicting the Phenomena of Swelling and Shrinking

V. EFFECT OF SOIL SWELLING

Changes in soil volume can have both negative and positive effects on the activities of human beings. The loss of property due to destruction of buildings, roads, and pipelines in uncropped soils, as well as the effect on agricultural production due to the leaching of fertilizers and chemicals below the depth of root zone through desiccation cracks, are some of the unfavorable effects caused due to pass flow and swell-shrink soils. Horizontal cracks occurring in the soils disrupt water flux in capillary pores. However, swelling clays can be utilized for sealing the hazardous waste landfills. This sealing prevents contaminants from migrating downwards into the groundwater. When cropped soils dry, there is improvement in the drainage of water and soil aeration and decrease of runoff in sloped areas due to the formation of a dense pattern of cracks. The improvement in porosity damages due to

compaction is closely related to soil cracking. Drying results in the development of tensile stress, which lead to the creation of primary, secondary and tertiary cracks. These cracks, then represent the void spaces and the walls of aggregates formed later on. This path is thought to restore the soil porosity in a layer of previously compacted soil.

VI. METHOD FOR ASSESSING THE SWELL-SHRINK POTENTIAL

Coefficient of Linear Extensibility (COLE) is one of the methods which helps in characterizing the variation in soil volume at 1/3rd atm. water retention, i.e. at field capacity to the oven dry condition.

$$\text{COLE} = (v_{1/3\text{atm}} - v_{\text{dry}})^{1/3} - 1$$

Where, $v_{1/3 \text{ atm.}}$ is the volume of soil at 1/3 atm. retention of water and v_{dry} is the volume of soil at conditions of oven drying. A range of shrink-swell potential of soil can be distinguished according to COLE:

| Swell-shrink potential of soil | COLE |
|---------------------------------------|-------------|
| Low | <0.03 |
| Moderate | 0.03 – 0.06 |
| High | 0.06 – 0.09 |
| Very High | >0.09 |

VII. CONCLUSION

The major geological hazards that afflict residential properties and other low-rise structures globally and cost billions of pounds each year are subsidence and heave caused due to shrink-swell soils. They cost property owners more money on an average each year than floods, earthquakes, landslides, hurricanes, and tornadoes all together. These soils play an important role in agricultural production since they provide enhanced entry of water to the soil through the cracks formation and also provide the subsoil with nutrients, but they pose some serious problems like damage to the plant roots, and leaching essential nutrients beyond the root zone, giving more surface for the soil moisture loss and thus help in promotion of rill erosion due to formation of cracks. Therefore, the behaviour of these swell-shrink soils should be understood well and managed accordingly in order to avoid the geological hazards and also for the sustenance of agricultural production system. The subsidence or heave caused due to the changes in water content of the soil should be kept fairly constant, and other factors like presence of tree roots, geology and clay minerology and climate should be addressed and studied well before conducting any research for agricultural production or getting them used for any infrastructure construction.

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